Coordinated Fibre Span Power Optimisation and ROADM Input Power Management Strategy for Optical Networks

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Abstract *A coordinated optical power optimisation strategy over per-fibre-span and ROADMs is proposed to increase the network throughput. The simulation shows the strategy can improve network throughput by 15%. The experiment demonstration verifies 0.7 dB SNR improvement per lightpath.*

Introduction

It is important to accurately model, monitor and manage the impairments in the future optical networks to meet the requirement of providing flexible, high bandwidth demands. Apart from impairments from optical links, it is also a great challenge to manage the impairments generated by reconfigurable optical add-drop multiplexers (ROADMs), due to the requirement of additional amplifiers to compensate the insertion loss[1].

In current optical networks, optical signal with a constant power is launched across multiple fibre spans and ROADMs, where any power loss is completely compensated by the amplifiers. The traditional approach cannot efficiently manage the impairments as it neglects the characteristics of different spans and ROADMs, such as fibre type, span length, loading condition due to add-drop, noise figure (NF) of amplifiers and insertion loss, making it inefficient use of the network. In the context of software-defined networking, the power of each span and ROADM can be dynamically optimised according to network status to improve network throughput.

Therefore, in this paper, a coordinated fibre span and ROADM input power optimisation strategy is proposed to minimize the nonlinearity (NLI) and ASE effect. We conduct the simulation to investigate the impact of network throughput using the proposed strategy. Moreover, we also build a field trial testbed to experimentally demonstrate its benefit. The simulation results show that network throughput can be improved by 15% adopting the proposed solution. Through the experiment, 0.7 dB improvement can be achieved through coordinated span and ROADM input power optimisation. The simulation and the experimental results indicate the proposed optimisation strategy can increase the SNR performance thus improve the network capacity.

Power Optimisation Model

We consider the ASE and NLI as the dominant impairments in the network. The ASE consists of the noise due to in-line amplification and compensation of ROADM insertion loss. The NLI is assumed to accumulate incoherently, and the end-to-end SNR at the receiver is calculated as[2]:

$$SNR^{-1} = \sum_{n}^{N_{rd}} \left(\frac{P^{rd}}{hvB \cdot 10^{\frac{NF_{rd}^{n}}{10}} \cdot IL_n} \right)^{-1} + \sum_{i}^{N_{sp}} \left(\frac{P_i}{hvB \cdot 10^{\frac{NF_i}{10}} \cdot LO_i + P_i^3 \cdot \chi_i} \right)^{-1} + SNR_{TRx,b2b}^{-1} \quad (1)$$

The first part of the Eq. (1) indicates the SNR degradation due to ROADM, where P^{rd} is the ROADM input power, NF_{rd}^{n} and IL_n the post-amplifier NF and insertion loss of the *n-th* ROADM respectively and N_{rd} is the ROADM number. The second part represents the SNR degradation due to in-line ASE and NLI, where P_i is the power of the *i-th* span, *h* the Planck constant, v the carrier frequency, NF_i and LO_i the NF of EDFA and linear loss of the *i-th* span respectively, N_{sp} the spans number and χ_i is the NLI coefficient determined by[3] using GN model[4]. The third part presents back-to-back SNR of the transceivers (TRx). In this paper, the impairments from TRx are not considered due to irrelevancy of the optimisation target.

From the Eq. (1), the SNR degradation due to ROADM insertion loss decreases as the P^{rd} increases. Therefore, increasing the ROADM input power improves the SNR performance. Despite optical signal passing through the ROADM transmitting in the linear regime, the NLI in the spans grows cubically as the signal power increases. Therefore, each span power can be optimised individually, which is expressed as:

$$P_i = \sqrt[3]{hvB \cdot 10^{\frac{NF_i}{10}} \cdot LO_i / (2 \cdot \chi_i)} \quad (2)$$

From the Eq. (2), the optimal power of each span does not only depend on its attenuation and the EDFA NF, but also relies on the load-dependent NLI coefficient χ_i. The optimal power is higher when the link is lightly loaded and the optimal power gradually reduces as link becomes congested. Therefore, we optimise the per span channel power using the Eq. (2) by considering the NF of EDFA, fibre attenuation and the loading condition of each span. We also set the signal power launching into ROADM with a sufficiently high value according to EDFA capability to reduce the impact of the ROADMs insertion loss.

Simulation Scenarios and Results

To evaluate the performance of the power optimisation strategy described previously, we use fixed launch power as the benchmark (BM). To make a fair comparison, the same ROADM input power is applied to the proposed strategy with the span power optimised (SPO) using Eq. (2). We consider the network operates in 4 THz bandwidth of C-band with 12.5 GHz grid. The ROADM insertion loss is assumed to be 14 dB and NF of the EDFA is set between 4.5 dB and 6.5 dB. We assume spans in the same link are of identical length with maximum span length of 60 km. The same set of fibre parameters are used as mentioned in[2]. To compare the impact of two strategies on the network throughput, we deploy traffic requests to the BT network[2] sequentially, which is shown in Fig. 1. Each request consists of a pair of randomly selected source-destination with bandwidth demand of 100 Gbps. For a request, we calculate a least congested path and search for the first-fit spectrum. 5000 traffic requests are randomly generated and loaded to the network sequentially. The results are averaged over the repeating the process 100 times for both BM and SPO.

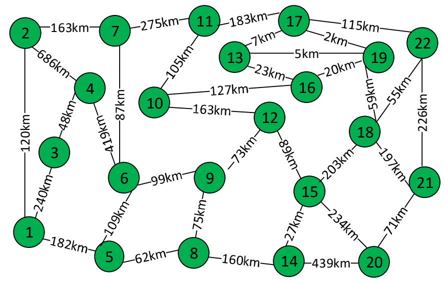

Fig. 1: British Telecom (BT) network topology with 22 nodes

The average network capacity of BM and SPO over the increasing ROADM PSD is shown in Fig. 2 when network blocking occurs. It can be seen that the optimal power spectral density (PSD) of BM is 12.6 mW/THz to achieve maximum network throughput. This is because the ROADM PSD is equivalent to the span PSD for BM. When PSD is low, the network works in the linear regime. Thus the SNR degradation due to fibre span and ROADM are both high. When PSD is high, the network operates towards the highly nonlinear regime. The advantage of less SNR degradation of ROADM collapses as the NLI dominates the performance. This leads to the increase of network capacity first and then decreasing against the increasing PSD.

Comparing the BM with SPO, SPO is able to yield 5 Tbps more capacity when ROADM PSD is 12.6 mW/THz, due to span power optimisation. When the ROADM PSD rises, SPO can further improve the capacity due to the reduced impact from ROADM, while remaining each span power optimised. SPO can theoretically achieve 402 Tbps when the ROADM input power is sufficiently high, making the impact of ROADM negligible. Comparing the performance of BM with SPO, the proposed SPO outperforms BM with additional 15% throughput, due to coordinated span and ROADM input power optimisation.

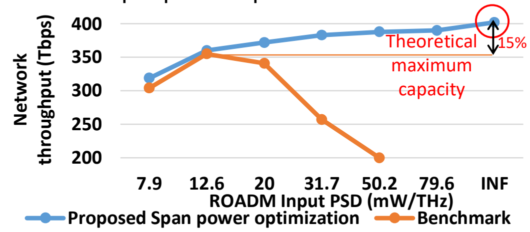

Fig. 2: Network throughput of BM and SPO when network blocking occurs

Experiment Scenarios and Results

Fig. 3 (a) shows a schematic of the experimental testbed setup for the proposed fibre span and ROADM input power optimisation. The testbed contains 314 km fibre in the lab and 236 km fibre as the part of the UK National Dark Fibre Infrastructure Service (NDFIS) between Bristol and Froxfield. The Voyager devices serve as coherent TRx. We use PM-16QAM signal with 25% FEC overhead and 0.3 roll-off factor root raised cosine match filter. The wavelength selective switches (WSS) are used to emulate the ROADMs in the network by adding additional 7 dB loss apart from their insertion loss.

Four 50 GHz spacing channels, namely Ch50 - Ch53 with frequency 193.6 THz - 193.75 THz respectively, are launched into the first link through WSS1. Another four channels (Ch48, 49, 54, 55) are added to the second link through WSS2 to emulate diverse loading conditions of different links. We first consider the case that each EDFA completely compensate the span loss and the WSS loss. The constant per channel launch power varies from -4 dBm to 5 dBm. The received SNR as a function of signal launch power of Ch51 and Ch52 is plotted in Fig. 3 (b). The SNR difference between two channels is due to the different performance of the two TRx. From Fig. 3 (b), it is observed that both channels achieve the highest SNR when the launch power is 0 dBm, which corresponds to 15.04 dB for Ch52 and 14.52 dB for Ch51. Therefore, two optimal SNR values are regarded as the benchmark for the span power optimisation.

We start the fibre span power optimisation from the first span. At each step, the power of the corresponding span is optimised according to the Eq. (2) considering the NF of corresponding EDFA, the span fibre attenuation and the channel loading status of the span, while the power of the following spans remains at 0 dBm. The SNR of Ch51 and Ch52 against the optimisation step are shown in Fig. 3 (c). The SNR performance of Ch52 is associated with the left axis, the SNR of

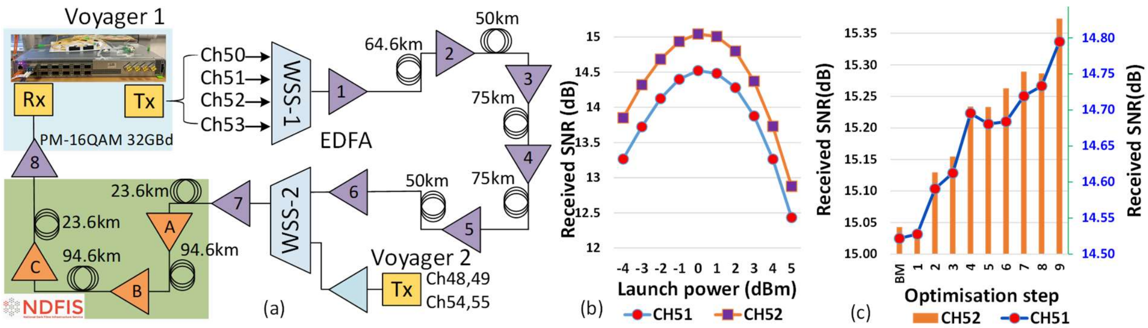

Fig. 3: a) Experimental testbed setup; b) Received SNR versus fixed signal launch power of benchmark; c) Received SNR improvement versus span level optimisation step.

Ch51 associated with the axis on the right. From Fig. 3 (c), the SNR of both channels improve with the increasing steps of optimisation. The span power optimisation strategy can achieve 0.33 dB and 0.29 dB SNR improvement for Ch52 and Ch51 respectively when all the optimisation steps are conducted.

After the span level power optimisation, we further investigate the impact of ROADM input power on the signal quality. As discussed in the previous section, the SNR increase as the output power of pre-amplifier (EDFA 6) increases. However, results in Fig. 4 (a) indicate that the SNR of both channels are not improving over the increasing ROADM input power. With rising output power of EDFA 6, the input power of EDFA 7 increases as well which decreases the gain of EDFA 7. The gain decline causes its noise figure (NF) rising dramatically, shown as the red curve in Fig. 4 (a). Therefore, the benefit of optimising the ROADM input power is lost due to more SNR degradation of the next span.

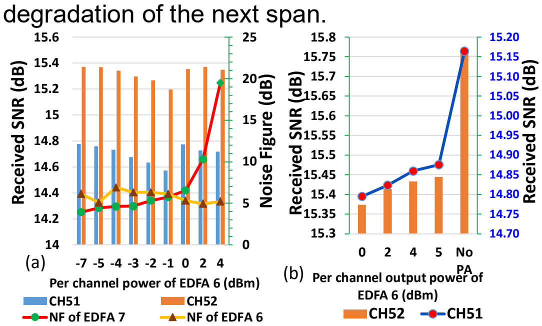

Fig. 4: a) SNR and noise figure versus the increasing per channel launch power of EDFA 6; b) SNR of two channels versus the increasing ROADM input power of solution 1 and removing PA in solution 2

To overcome the NF rising problem of the post-amplifier (PA), two solutions are proposed: 1) adding an attenuator at the output of the PA (EDFA 7); and 2) removing the PA by further increasing the gain of pre-amplifier. By placing an attenuator, the PA can operate in high gain mode with low NF. The attenuator is then adjusted to ensure the optimal power in the following span. Therefore, the proposed benefit of decreasing ROADM SNR degradation can be achieved. In solution 2, the pre-amplifier provides a sufficiently high power so that the WSS can directly adjust it to the optimal power of the following span. The SNR of both solutions are shown in Fig. 4 (b). It shows the SNR of both channels improve around 0.1 dB compared to span-optimised-only network when the ROADM input power increases from 0 dBm to 5 dBm using solution 1. Fig. 4 (b) also depicts around 0.4 dB improvement respectively for Ch51 and Ch52 by removing the PA. Therefore, combining span power optimisation and ROADM input power management solution, 0.7 dB improvement can be achieved.

Conclusion

In this work, we proposed a coordinated fibre span power optimisation and ROADM input power management strategy to improve the network capacity. Our simulation shows that the combined optimisation method outperforms the regular optimisation strategy by 15%. The experiment results demonstrate 0.7 dB SNR improvement using the proposed strategy.

Acknowledgements

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